

THE VOLATILE COMPOSITION OF THE SPLIT ECLIPTIC COMET 73P/SCHWASSMANN-WACHMANN 3: A COMPARISON OF FRAGMENTS C AND B

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ABSTRACT

The composition of fragments C and B of the Jupiter-family comet 73P/Schwassmann-Wachmann 3 (SW3) was investigated in early April of 2006 at IR wavelengths using high-dispersion echelle spectroscopy. Both fragments were depleted in ethane, and C was depleted in most forms of volatile carbon. In particular, fragment C shows a severe depletion of CH₃OH but a “normal” abundance of HCN (which has a similar volatility). Thermal processing is a possible explanation, but since fragment B is perhaps sublimating fresher material because of the frequent outbursts and fragmentation, the observed depletions might have cosmogonic implications. The chemistry of the volatile ices in SW3, like in the Oort Cloud comet C/1999 S4 (LINEAR), may be associated with sublimation of icy mantles from precometary grains followed by subsequent gas-phase chemistry and recondensation.

Subject headings: comets: individual (73P/SW3) — Kuiper Belt — solar system: formation

1. INTRODUCTION

As icy remnants of our early solar system, comets are central to understanding its origin and formation. They are believed to have formed coevally with the solar system during the collapse of the molecular cloud core, but the detailed volatile chemistry might depend greatly on the time and place of formation. Comets were ejected from their natal regions through dynamical interactions initiated by the young giant planets, and they are now found in two principal dynamical reservoirs⁷—the Oort Cloud and the Kuiper Belt—where they reside for most of their lifetimes (Stern 2003; Gladman 2005). Individual comets from either reservoir can be perturbed toward the inner solar system by various gravitational effects. As a comet approaches the Sun, its volatiles are released into the expanding coma where they can be sensed spectroscopically through their fluorescent rovibrational transitions at wavelengths $\lambda \sim 2\text{--}5\ \mu\text{m}$.

Chemical homogeneity among comets from a given reservoir is clouded by the expected radial migration of cometsimals within the protoplanetary disk and the scattering of comet nuclei through interactions with the giant planets (e.g., Levison & Morbidelli 2003; Gomes et al. 2005). This scenario is supported by the chemical diversity observed in comets from the same dynamical reservoir, in both parent (e.g., Biver et al. 2002; Mumma et al. 2003) and daughter (A’Hearn et al. 1995; Fink & Hicks 1996) volatile abundances.

The chemical composition of Kuiper Belt objects (KBOs) can be explored through observations of Jupiter-family comets (JFCs) whose primary dynamical reservoir is the scattered Kuiper disk (Bernstein et al. 2004). However, many JFCs have

experienced numerous passages near the Sun and therefore may have surface layers depleted in hypervolatiles. The recently split JFC comet 73P/Schwassmann-Wachmann 3 (hereafter SW3) provided us with a unique opportunity to measure the chemical composition of material issuing from the presplit interior, a (presumably) less processed region.

In 1995 while reaching perihelion, SW3 brightened greatly between September 5 and 8 (Crovisier et al. 1996), and the first breakup occurred approximately 6 weeks later (Sekanina 1996). Three brightness condensations were found (Boenhardt & Kaufl 1995) in images taken on December 12–13, and several others were found thereafter. The current apparition (two orbital periods after the observed initial splitting) showed the comet to be rapidly disintegrating with over 60 fragments stretching several degrees across the sky (Weaver 2006). Splitting or disintegration events have also been studied in comets from the Oort Cloud reservoir, e.g., C/1999 S4 (Mumma et al. 2001) and C/2001 A2 (Magee-Sauer et al. 2006), affording us the opportunity to compare and contrast the interior composition of gas and dust for bodies from these distinct reservoirs. A comparison with material ejected from the *Deep Impact* target comet is also relevant.

2. SURVEYS OF PARENT VOLATILES IN OORT CLOUD AND JUPITER-FAMILY COMETS

The level of thermal processing in cometary ices can be assessed by sampling species of different volatility (e.g., CO, CH₄, and C₂H₆). Our measurements of parent volatiles in Oort Cloud (OC) comets demonstrate that the hypervolatiles CO (DiSanti et al. 2001, 2003; Mumma et al. 2001) and CH₄ (Gibb et al. 2003) show extreme variability among comets (CO and CH₄ vary by more than a factor of 10, with no apparent correlation between them).

By contrast, the C₂H₆ mixing ratio is notably constant (0.6%) in our sample of eight OC comets. Two exceptions were found: C/2001 A2 (1.6%; Magee-Sauer et al. 2006) and D/1999 S4, a comet that was depleted in most forms of volatile carbon, including ethane (0.11%; Mumma et al. 2001). Biver et al. (2006) suggested that C/2000 WM₁ could be a second member of the depleted group.

Compared with OC comets, ecliptic comets (JFCs) have been underrepresented in surveys of parent volatiles due to their

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⁷ A third reservoir was suggested very recently, but its significance has not yet been assessed (Huu & Jewitt 2006).

generally lower molecular productivity (and hence weaker spectral lines). Comet 2P/Encke was the first ecliptic comet whose parent volatile composition was comprehensively sampled at infrared wavelengths (Dello Russo et al. 2004), and 9P/Tempel 1 (9P/T1) was the second (Mumma et al. 2005). Another JFC (21P/Giacobini-Zinner [21P/GZ]) was partially characterized using CSHELL (Mumma et al. 2000; Weaver et al. 1999). The *Deep Impact* mission revealed that the excavated material of JFC comet 9P/T1 had a mixing ratio of C_2H_6 (0.6%) similar to the dominant OC comets in our sample (Mumma et al. 2003, 2005). However, the preimpact value in 9P/T1 (0.2%) was a factor of about 3 lower, and similar to 2P/Encke and 21P/GZ, suggesting a high level of thermal processing on the surface of short-period comets.

The freshly exposed ice layers resulting from the recent (and ongoing) fragmentation of SW3 likely reveal the internal composition of the presplit nucleus. Through comparison with the chemical taxonomy of comets from the two principal reservoirs, we further test the hypothesis that volatiles of JF and OC comets originated in a common region of the protoplanetary disk. Here we report detections of H_2O , HCN, C_2H_6 , and C_2H_2 in component C and H_2O in component B of comet SW3. We also present sensitive upper limits for CH_3OH , CH_4 , and H_2CO in C and for HCN and C_2H_6 in B.

3. OBSERVATIONS

The composition of two SW3 components (C and B) was investigated using the near-infrared cross-dispersed echelle spectrometer (NIRSPEC) at Keck II (McLean et al. 1998) located on Mauna Kea, Hawaii. The instrument provides long-slit spectra with high spatial resolution about the cometary nucleus ($0''.2 \text{ pixel}^{-1}$) and sufficient spectral resolving power ($\lambda/\delta\lambda \sim 25,000$ for the $0''.43$ -wide slit) to conduct studies of individual spectral line intensities. Two echelle/cross-disperser configurations (denoted KL1 and KL2) were required to measure the various parent volatiles. The KL1 setting encompassed H_2O , C_2H_6 , and CH_3OH , and KL2 sampled H_2O , HCN, CH_4 , and H_2CO (see Blake et al. 2006).

Component C was observed on April 7 and 16 (UT dates). On April 7, we acquired 20 minutes on-source with KL1 and 16 minutes using KL2; on April 16 we used KL2 (20 minutes on-source). Early in April, component B experienced an outburst and brightened greatly, reaching a magnitude of 9 on April 12 (as bright as the main component C; see IAU comet magnitudes⁸). We observed fragment B on April 15 using KL1 (28 minutes on-source) and KL2 (24 minutes on-source). The weather conditions during the observations were favorable (i.e., no clouds), with 0.5 precipitable millimeters (pr-mm) of water on April 7 and ~ 2 pr-mm of water on April 15 and 17.

The spectra were acquired by nodding the telescope along the slit in an ABBA sequence, with the two beams separated by $12''$ (half the slit length). At each grating setting, spectra of infrared standard stars and calibration frames (flats and darks) were acquired for absolute flux calibration of the cometary data. We followed our standard methodology for data reduction and analysis of the individual echelle orders (Bonev 2005; DiSanti et al. 2001; Mumma et al. 2001). The signal from the two beams was combined, and spectra were extracted over nine rows ($1''.78$) centered on the nucleus, taken to be the row containing the peak continuum and gas intensity (Fig. 1). Cometary molecular emissions were isolated from the dust continuum emission by subtracting a modeled continuum multiplied by

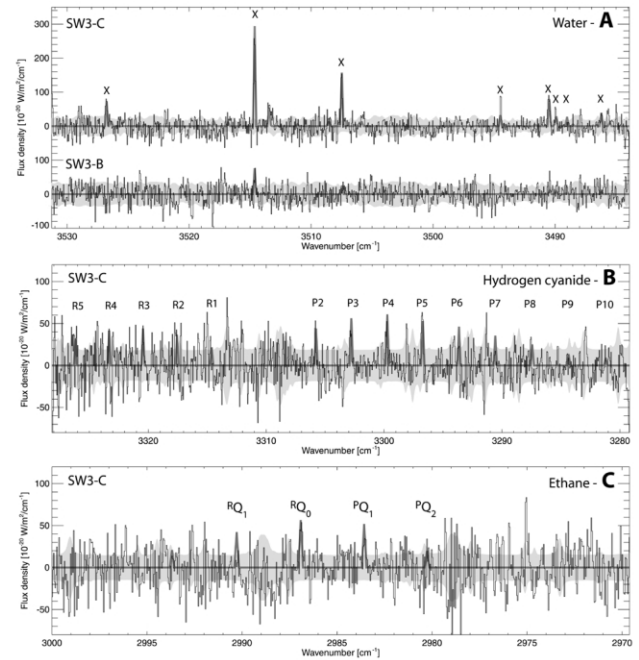


FIG. 1.—Spectral residuals of parent volatiles detected in comet SW3, after subtracting a modeled continuum. The light-gray background represents the 2σ stochastic noise envelope of the measurement. In all panels, the heavy gray line corresponds to the modeled molecular emission multiplied by atmospheric transmittance and convolved to the instrumental resolving power ($\lambda/\Delta\lambda \sim 2.5 \times 10^4$). (A) Setting KL1, order 27: water in fragments C and B. (B) Setting KL2, order 25: hydrogen cyanide (ν_3 band) in fragment C. (D) Setting KL1, order 23: ethane (ν_7 band) in fragment C.

the atmospheric transmittance. The spectral transmittance was synthesized using the GENLN2 version 3 line-by-line model (Edwards 1992), which accesses the HITRAN-2004 Molecular Database (Rothman et al. 2005, with the updated C_2H_6 ν_7 band).

4. PRODUCTION RATES

We followed our established methodology (e.g., Bonev 2005; DiSanti et al. 2001) to retrieve production rates from observed line intensities (corrected for atmospheric transmittance) using g -factors appropriate to the measured rotational temperature (Table 1). We assumed an isotropic cometary outflow with a constant radial velocity and that parent volatiles coming off the nucleus decay exponentially toward the daughter species. The uncertainties given in Table 1 reflect the level of agreement between production rates obtained independently from different lines of the same species. In addition, we verified that the reported values are (at worst) only weakly influenced by the uncertainties in rotational temperature.

Rotational temperatures were obtained by correlation and excitation analyses as described by DiSanti et al. (2006), Bonev (2005), and Dello Russo et al. (2004). Setting KL1 samples H_2O lines of fairly low rotational excitation, so they usefully constrain the lower bounds for T_{rot} —they are not useful indicators for temperatures higher than 50–70 K. By contrast, setting KL2 samples a number of lines of high rotational excitation (which were not detected), thereby bounding the high-temperature end of acceptable T_{rot} values. Table 1 also shows rotational temperatures determined independently for HCN (component C only), and they agree with the results for H_2O . For component B, a rotational temperature of 20 K provided optimal consistency among H_2O lines measured in the two instrument settings (KL1 and KL2). When T_{rot} could not be constrained, we adopted the value given in parentheses.

⁸ See <http://cfa-www.harvard.edu/cfa/ps/icq/CometMags.html>.

TABLE 1
THE PARENT VOLATILE COMPOSITION OF COMET 73P/SCHWASSMANN-WACHMANN C AND B AS MEASURED WITH NIRSPEC IN 2006 APRIL

Species	Frag.	T_{rot} (K)	ν_0 (cm^{-1})	Lines Sampled	Q (10^{25} s^{-1})	Mixing Ratio (%)
UT 2006 April 7						
H ₂ O (KL1 and KL2)	C	55^{+10}_{-10}	...	54	590 ± 60	100.0
KL1 (09:37–10:07): ^a						
C ₂ H ₆	C	(55)	2986	2	0.9 ± 0.2	0.15 ± 0.04
CH ₃ OH	C	(55)	2844	Multiple	<3.0	<0.51
KL2 (10:41–11:04): ^b						
HCN	C	52^{+15}_{-10}	3303	14	1.0 ± 0.1	0.17 ± 0.02
CH ₄	C	(55)	3038	3	<1.5	<0.25
H ₂ CO	C	(55)	2910	Multiple	<3.0	<0.51
UT 2006 April 15						
H ₂ O (KL1 and KL2)	B	20^{+40}_{-5}	...	24	100 ± 20	100.0
KL1 (09:01–09:42): ^c						
C ₂ H ₆	B	(20)	2986	3	<0.3	<0.3
KL2 (10:24–10:58): ^d						
HCN	B	(20)	3308	9	<0.2	<0.2
UT 2006 April 16						
KL2 (08:42–09:11): ^e						
H ₂ O (order 26)	C	60^{+15}_{-20}	3435	24	620 ± 80	100.0
HCN	C	53^{+18}_{-10}	3303	14	1.3 ± 0.2	0.21 ± 0.04
C ₂ H ₂	C	(53)	3300	2	1.4 ± 0.3	0.23 ± 0.06
CH ₄	C	(60)	3038	3	<2.4	<0.39
H ₂ CO	C	(60)	2910	Multiple	<3.0	<0.48

NOTE.—The reported water production rate for April 7 was retrieved from three spectral orders (KL1 order 26/order 27 and KL2 order 26), and that for April 15 was retrieved from two spectral orders (KL1 order 27 and KL2 order 26).

^a $r_h = 1.271$ AU, $\Delta = 0.325$ AU, $v = -16.71$ km s⁻¹.

^b $r_h = 1.270$ AU, $\Delta = 0.325$ AU, $v = -16.61$ km s⁻¹.

^c $r_h = 1.210$ AU, $\Delta = 0.258$ AU, $v = -15.29$ km s⁻¹.

^d $r_h = 1.210$ AU, $\Delta = 0.257$ AU, $v = -15.17$ km s⁻¹.

^e $r_h = 1.194$ AU, $\Delta = 0.242$ AU, $v = -15.23$ km s⁻¹.

The measured water production rates for component C on April 7 and 16 indicate stable outgassing (Table 1). Component B, however, experienced a major outburst and ongoing fragmentations during this interval as revealed by photometric observations (see IAU comet magnitudes) and high-resolution imaging (Weaver 2006). This behavior suggests that B successively revealed newly exposed ice layers, probably consisting of less thermally processed material from the interior of the presplit nucleus.

Of the hypervolatiles, we obtained stringent upper limits for CH₄ in component C by searching for the three strongest lines (R0, R1, and R2 of the ν_3 band). The obtained mixing ratios relative to water (<0.25% on April 7 and <0.39% on April 16) fall near the low end among comets sampled (0.2%–1.4%; Gibb et al. 2003). We detected ethane (two Q -branches of the ν_7 band) on April 7 in component C, and we obtained upper limits on April 15 for component B. In both fragments, the C₂H₆/H₂O ratio was much lower than the value for most other comets (Table 1). However, the abundance ratio of acetylene for component C (~0.2%) falls within the range observed in other comets (see § 5). Of the high-temperature volatiles that likely would not be affected by thermal processing, we detected several lines of HCN (ν_3 band), and its relative abundance is similar to that found in 9P/T1 (JFC) and other comets. By contrast, CH₃OH is highly depleted even though its volatility is similar to that of HCN. Although no strong emission is seen in the Q -branch of the ν_3 band, some excess flux is found at the proper frequency. The 3σ upper limit [$Q(\text{CH}_3\text{OH}) < 3 \times 10^{25} \text{ s}^{-1}$] represents a relative abundance lower than 0.5%, in the lower end of the range observed among comets (Mumma et al. 2003; Biver et al. 2002).

5. DISCUSSION

The chemical taxonomy of fragments B and C as retrieved from our IR observations shows a severe depletion in most forms of volatile carbon, consistent with optical spectroscopic observations in March by Schleicher (2006).

Our current knowledge of the parent volatile composition of Jupiter-family comets is still limited. The abundance of ethane relative to water was low (0.2%) in comets 21P/GZ (Mumma et al. 2000) and 9P/T1 (preimpact; Mumma et al. 2005), and is comparable to our current measurements of two fragments of SW3 (~0.2%). By contrast, ethane was much higher (C₂H₆/H₂O ~ 0.6%) in material ejected from 9P/T1 by *Deep Impact* (Mumma et al. 2005). Clearly, the material seen in SW3 and in the 9P/T1 ejecta experienced different histories, whether in the nebula (cosmogony) or later in the cometary nucleus (fractionation by thermal processing).

According to the thermal processing hypothesis, the surface layer of a cometary nucleus is preferentially depleted in the more volatile species owing to insolation received on previous orbits; JFCs may be especially susceptible owing to their short-period orbits. If 21P/GZ and 9P/T1 (preimpact) show low C₂H₆/H₂O for this reason, the 9P/T1 (ejecta) and SW3 results are puzzling. The *Deep Impact* results suggest that the depleted region is likely restricted to depths less than 20 cm (Groussin et al. 2007). The splitting of SW3 in 1995 (and its continuing fragmentation today) exposed ices that once lay deep within the presplit nucleus; the severe depletion in C₂H₆/H₂O then is difficult to reconcile with the thermal fractionation model. These diverse observations could be reconciled if thermal fractionation depths vary widely among JFCs.

In the cosmogonic hypothesis, the composition of SW3 reflects its formation at a different place and/or time in the solar nebula than the high ethane comets, including 9P/T1. If C_2H_6 is produced mainly from C_2H_2 through hydrogenation on grain surfaces (Gail 2002; Mumma et al. 1996; Charnley et al. 1995; Tielens & Allamandola 1987) and a constant initial supply of C_2H_2 is assumed, then ethane production is constrained to a “cold” nebular region rich in H atoms. The conversion efficiency ($C_2H_2 \rightarrow C_2H_6$) depends then on (1) the density of H atoms (which is directly related to the local X-ray flux through photoionization of nebular H_2 followed by H-atom production via recombination reactions) and (2) the local temperature (since these H atoms must be retained on the icy grain surface for a sufficiently long time to permit hydrogenation reactions).

If SW3 and 9P/T1 formed coevally before the nebula cleared, SW3 might have formed in the outer regions of the protoplanetary disk where the increased attenuation of X-rays with greater heliocentric distance reduced the hydrogenation efficiency. 9P/T1 could have formed at a smaller heliocentric distance where the local X-ray flux was higher.

Alternatively, both could have formed in the “cold” outer solar system, but with 9P/T1 forming later than SW3, when X-rays penetrated to larger heliocentric distances due to partial clearing of the nebula, resulting in higher H-atom densities and more efficient hydrogenation of C_2H_2 . Methanol can also be efficiently produced through conversion of condensed phase CO through H-atom addition reactions on grain surfaces (Watanabe et al. 2004; Hudson & Moore 1999), so these possible time/place scenarios for the formation of SW3 might also explain the observed depletion (Table 1).

A third hypothesis is that the unusual chemistry of these volatiles may be associated with sublimation of icy mantles from precometary grains followed by subsequent gas-phase chemistry and recondensation. The observed taxonomy of comet SW3 is similar to that of the OC comet C/1999 S4. Both comets are depleted in most forms of volatile carbon, and, in particular, they show a severe depletion of CH_3OH with a “normal” abundance of HCN (which has a similar volatility). As argued by Mumma

et al. (2001) for C/1999 S4, a possible mechanism for explaining the observed dichotomy may lie in chemical processing before accumulation into precometary grains. Models of gas-phase chemistry in hot cores predict different paths for CH_3OH and HCN, with the methanol lifetime being much shorter (Charnley et al. 1992). Like HCN, H_2S is long-lived in hot cores (Hatchell et al. 1998), so its abundance in SW3, along with molecules related to the synthesis of methanol through grain surface chemistry, e.g., CO and H_2CO (Hidaka et al. 2004; Tielens & Allamandola 1987), would further test the relevance of gas-phase chemistry in controlling the volatile composition.

Measuring the volatile composition for a statistically significant number of Oort Cloud and scattered Kuiper disk comets (JFCs) will help us clarify the origin of comets in each reservoir. We note that a shared origin for some comets presently residing in the Oort Cloud and in the scattered Kuiper disk has been strongly suggested by recent dynamical models (Gomes et al. 2005). A cometary taxonomy based on composition could provide important tests of dynamical models that invoke significant radial migration of cometesimals prior to their accumulation into the final cometary nuclei and ejection to their present-day reservoirs.

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